

# Summary of Thrusts 16-18

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Theme 5: Optimizing the Magnetic Configuration



## Theme 5 represents the fusion science and technology opportunities in toroidal alternates

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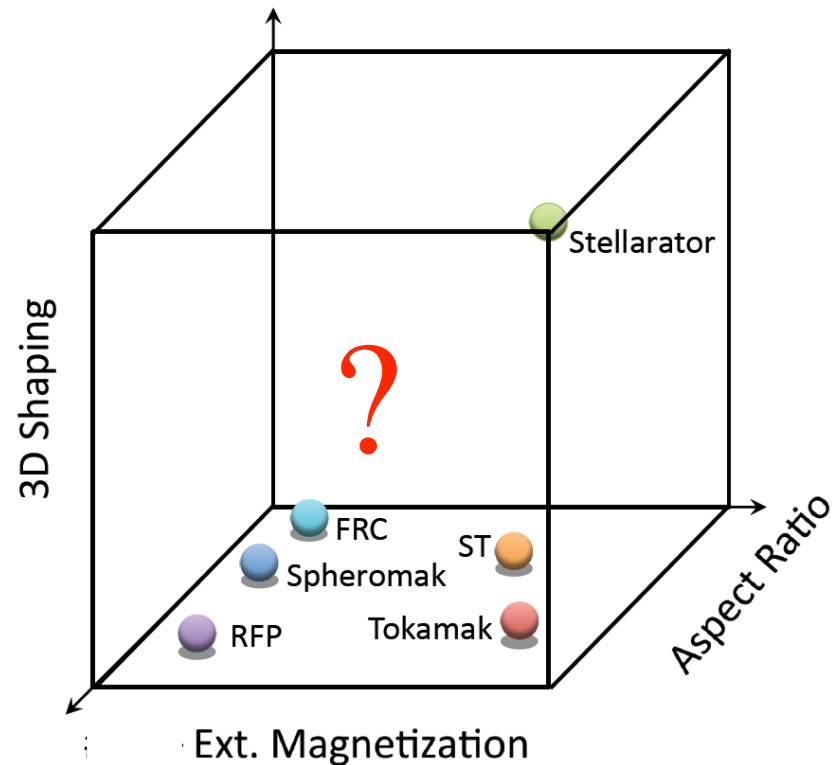
- Five major toroidal alternates were examined by FESAC Toroidal Alternates Panel (TAP), with focus on goals for the ITER era
  - Stellarator
  - Spherical Torus (ST)
  - Reversed Field Pinch (RFP)
  - Compact Torus (CT):
    - Field Reversed Configuration (FRC)
    - Spheromak
- Each configuration offers particular strengths for fusion development. Each requires a self-consistent and unique set of solutions to general scientific issues, e.g., confinement, stability, sustainment, controlled boundary interface, etc.
- Research on multiple magnetic configurations collectively advances and validates our understanding of fusion plasma science and technology

# Thrusts 16-18 advance configuration optimization

16. Developing the spherical torus to advance fusion nuclear science
17. Optimize steady-state, disruption-free plasma confinement using 3D magnetic shaping, emphasizing quasi-symmetry principles
18. Achieve high performance plasma confinement using minimal externally applied magnetic field

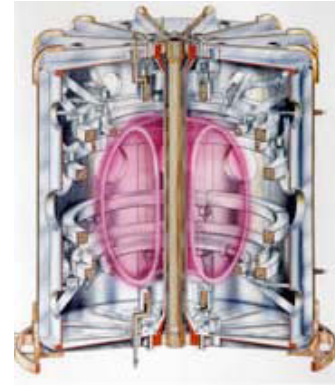
“spots” represent typical or historical view of the configurations

optimized configurations exist in this space



# 16. Developing the spherical torus to advance fusion nuclear science

- The ST (low aspect ratio tokamak) program is poised to generate the knowledge to construct a fusion nuclear science and technology component testing device, and to aggressively pursue improvements to advance the ST for energy production
- Thrust builds on recent advances
  - Non-solenoidal current initiation (25% of required value)
  - Favorable dependence of confinement on the magnetic field
  - Sustained stability at beta required for Component Test Facility
  - Test bed for liquid lithium walls, demonstrating improved confinement



## Key issues

- The ST has little room for a central solenoid to produce and drive plasma current.
- The compact geometry increases the heat loading to the wall.
- ST energy confinement behaves differently than in a higher aspect ratio tokamak.
- Broad current profiles and near-spherical geometry strongly impact stability.
- The lower magnetic field and enhanced energetic particle drive of the ST may challenge the sustainment of high plasma current.
- The compact geometry precludes the use of shielded superconducting magnets.

# 16. Developing the spherical torus to advance fusion nuclear science

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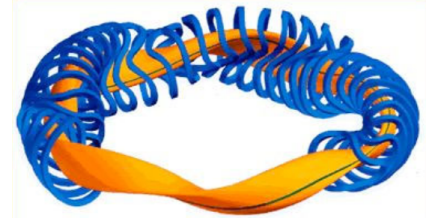
## Proposed actions in thrust:

- Exploit and understand magnetic turbulence, electromagnetic waves, and energetic particles for MA plasma current formation and ramp-up.
- Develop innovative magnetic geometries and first wall solutions such as liquid metals to accommodate multi-MW/m<sup>2</sup> head loads.
- Utilize upgraded facilities to increase plasma temperature and magnetic field to understand ST confinement and stability to fusion-relevant parameters.
- Implement and understand active and passive control techniques to enable long-pulse disruption-free operation in plasmas with very broad current profiles.
- Employ energetic particle beams, plasma waves, particle control, and core fueling techniques to maintain the current, and control the plasma profiles.
- Develop normally-conducting radiation-tolerant magnets for low aspect ratio applications.
- Extend ST experiments to near burning-plasma conditions in a new or upgraded device.

## 17. Optimize steady-state, disruption-free toroidal confinement using 3D magnetic shaping, emphasizing quasi-symmetry principles

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- The stellarator concept, and more generally 3D flux surface shaping, provides the only validated means of disruption free, sustained high plasma pressure with tokamak-like confinement.
  - Intrinsically steady-state
  - No disruptions in routine operation
  - Fusion-relevant performance: good confinement, high plasma pressure, densities above the empirical tokamak limits, and long sustainment.
  - Understanding 3D shaping physics is a core competence for mag. fusion
- Thrust builds on U.S. leadership in the development of quasi-symmetry



### Key issues

- How much 3D shaping is required to attain simultaneous sustained good confinement at high pressure and temperature without disruptions.
- 3D shaping requires magnets that are more complex than planar coils.
- Divertor designs for 3D magnetic fields are geometrically more complicated, but offer lower plasma edge temperatures and higher density which eases power handling.

## 17. Optimize steady-state, disruption-free toroidal confinement using 3D magnetic shaping, emphasizing quasi-symmetry principles

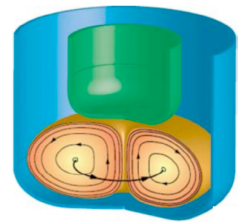
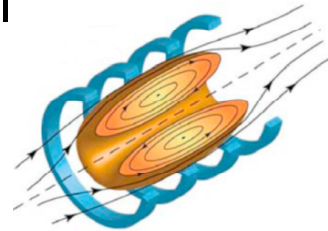
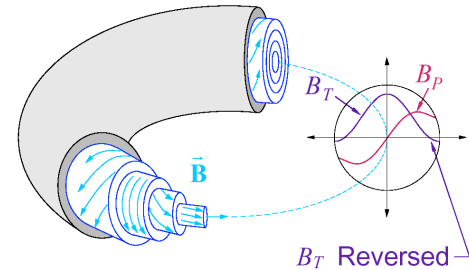
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### Proposed actions in thrust:

- Build quasi-symmetric configurations with plasma parameters sufficient to demonstrate low collisionality, disruption-free operation at high plasma pressure. Will extend understanding of plasma flow, turbulent transport, divertors, energetic particle confinement, and impurity transport to quasi-symmetric fields
- Expand efforts in non-axisymmetric theory and modeling, which is crucial to the full range of applications of 3D magnetic fields
- Design quasi-symmetric configurations with simpler and maintainable magnet systems
- Increase participation on the large stellarator experiments in Japan and Germany, particularly to understand 3D divertor physics and design, and impurity transport
- Determine the level of 3D shaping needed to eliminate disruptions in tokamaks
- Explore the additional application of 3D shaping to other magnetic configurations, such as RFPs, and CTs.
- Building on actions above, conduct an integrated quasi-symmetric experiment which will validate extrapolation of 3D shaping to burning plasma applications

# 18. Achieve high performance toroidal confinement using minimal externally applied magnetic field

- By requiring less external magnetization, the RFP, spheromak, and FRC represent potentially high payoff options for the fusion energy program.
  - Modest magnets reduce engineering challenges
  - High beta 10-80%, and large Ohmic heating
  - FRC and spheromak approach cylindrical geometry
- Thrust builds on recent advances, especially the use of control techniques to improve confinement and stability
- Broad scientific impact
  - Physics connections to space and astrophysical plasmas
  - Versatile laboratories for fusion, basic science, and education



## Key issues

- Understanding confinement and stability in reactor-relevant conditions.
- Configurations must be formed and sustained efficiently.
- The compatibility of confinement, sustainment, and plasma-boundary control must be demonstrated.

# 18. Achieve high performance toroidal confinement using minimal externally applied magnetic field

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## Proposed actions in thrust:

- Develop and deploy plasma diagnostics to understand transport and stability
- Apply theoretical and computational models to analyze nonlinear effects. Validate models through comparison with improved measurements.
- Study FRC stability at small ion gyro-radius in a new or upgraded facility with energetic ion sources. Success will enable integrated tests of stability, confinement, and sustainment.
- Develop improved current sustainment methods for the spheromak. Small experiments will feed transformational ideas to a larger facility to test integrated confinement and sustainment.
- Extend confinement scaling and demonstrate current sustainment at high temperature in a new large current RFP. A staged, upgradeable facility would eventually demonstrate near-burning plasma conditions with integrated plasma-boundary and MHD stability control.
- Quantify the benefits of low-field, steady-state or pulsed reactors using system studies.